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ORIGINAL ARTICLE

Performance evaluation of three different types of local evaporative cooling pads in greenhouses in Sudan

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Abstract This study was conducted in Date Palm Technology Company Limited, Shambat, Khartoum State. To evaluate performance of three types of evaporative cooling pads for greenhouses (celdek pads, straw pads and sliced wood pads), as compared to the conditions outside the greenhouses (control), for pads. Performance evaluation includes environmental parameters (temperature and relative humidity at 8 am, 1 pm and 6 pm) and crop parameters (length and stem diameter, leaves number and width, fruit length and diameter, fruit weight and dry matter and yield). The results obtained for the temperature at 8 am showed that there was no significant difference (0.05) inside the greenhouses, while a high significant difference between the conditions inside and outside of the greenhouses was found. Significant differences were found at 1 pm and 6 pm between all treatments as compared to the conditions outside the greenhouses, and the results obtained for relative humidity showed high significant differences at 8 am and 1 pm inside the greenhouses and between inside and outside the greenhouse, respectively, while there was no significant difference at 6 pm inside the greenhouses and between inside and outside the greenhouses. On the other hand, the results obtained for crop parameters showed that there were significant differences between all parameters inside the greenhouses and outside the greenhouses; however, the greenhouses with sliced wood pads gave the highest yield and the greenhouses with straw pads gave the least and conditions outside gave the lowest.

This study indicated that the sliced wood pads are better than the other evaporative cooling pads.

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1. Introduction

In a greenhouse system the growth conditions are usually achieved through monitoring of all effective growth factors, such as carbon dioxide concentration, temperature, relative humidity, light and radiation. In fact, greenhouse agriculture offers better chances for off-season production of many crops (Ernst, 2004).

The procedure of evaporative cooling has been used to improve human, plant and animals comfort conditions for the long time in the thermal environmental control applications. It remains one of the least exclusive techniques to get dry-bulb temperature to a more comfortable range. Evaporative cooling has also many practical applications in agriculture. It has been become average for many poultry houses and greenhouses and is used for swine and dairy cattle.

The principle of evaporative cooling reveals that the evaporative cooling system can only remove room sensible heat; therefore, the evaporative cooling system works finest in hot and dry climate where the maximum evaporative cooling will result (Chung et al., 2010).

It is a reliable method and requires minimum power consumption. To reduce temperature, in tropical and sub-tropical climates, has challenged the agricultural industry. The production rate of plants and livestock in these regions has been suppressed by the high temperatures and dry weather (Mohammed and Abdulelah, 2005).

Manufactures have tried pad materials of wood, metal, mineral, glass, plastic and cement. More newly, new cellulose paper designs have been developed to make evaporative cooling more competent and more valuable in different applications including industrial and built-up sectors, greenhouses, beef, poultry, and swine buildings, as well as storage warehouses. These commercially available pads are usually used in thickness ranging from 10 to 30 cm and are expensive per unit area (Chung et al., 2010).

Generally, Sudan weather conditions are characterized by having predominantly long and hot summers and short and mild winters. Such climatic conditions put a great strain on the types of crops that could be successfully grown. This is very much true with most horticultural vegetables.

With the increasing demand for many of the vegetables, such as tomato, potato, cucumber, etc., the need became urgent for their off-season production. Many attempts were made in this regard including the use of different types of evaporative cooling pads to reduce the temperature and alter relative humidity in greenhouses. However, their performance was not critically evaluated.

This research work attempts to evaluate the performance of three commonly used evaporative cooling pads (celdek, straw and sliced wood) during the summer season, with regard to their effect on the environment inside greenhouses and on the performance of an off-seasonally grown test crop.

To evaluate the effect of the different evaporative cooling pads on temperature and relative humidity of plastic film tunnel greenhouses under exhaust fan.

To use a test crop to evaluate the effectiveness of the evaporative cooling pads on off-season crop production.

2. Materials and methods

The experiments were conducted in the Date Palm Technology Company Farm in Shambat town, Khartoum State (15°40′N, 32°32′E, 380 m above sea level). To achieve the objectives of this research endeavor an experiment was carried out to evaluate the effects on temperature, relative humidity of greenhouses when using different types of evaporative cooling pads during the summer period.

The experimental work was mainly concerned about evaluating the performance of three types of evaporative cooling pads (namely: celdek cellulose, straw fiber and sliced wood) when used to change environmental conditions inside plastic-film greenhouses with the purpose of off-season growing of crops.

The experimental work involved measurement of both environmental parameters (temperature, relative humidity at different times of the day [8 am, 1 pm and 6 pm]) and crop parameters (length and diameter of stem, number and width of leaves, and length and diameter of fresh fruits and weight of dry matter and crop yield).

The statistical design used the Complete Randomize Design (CRD) coupled with Duncan's multiple range tests for the means separation test.

The three types of evaporative cool pad treatments were tested for temperature and relative humidity at 8 am, 1 pm and 6 pm each day for the duration of days which constituted the growing season of the test crop. Moreover, the temperature and relative humidity outside of the greenhouses were measured.

The test crop was sown during the summer season, in and outside the greenhouses, on ridges 50 cm apart. Two seeds were placed in a hole, and the space between the holes was 50 cm. Each location of the holes was irrigated by a drip irrigation nozzle from the drip irrigation pipe. The crop commenced to germinate after 3–5 days from sowing date, flowered after 21 days, and fruited after 45 days. The crop was harvested 6–7 times during its growing season.

2.1. Data collection

To evaluate the effectiveness of the evaporative cooling pad systems under test, the following data were collected:

Temperature and relative humidity inside the greenhouse at 8 am, 1 pm and 6 pm, throughout the growing season were collected.

Cooling efficiency, this is defined as the ratio of the actual dry-bulb temperature reduction to the theoretical maximum at 100% saturation (ASHARE, 1997). It is calculated as per the following equation:

$$\mu = \frac{(\mathrm{Tai} - \mathrm{Tao})}{(\mathrm{Tai} - \mathrm{Tas})} \times 100 \quad (1)$$

where μ is the cooling efficiency (%); Tai the air-in temperature (°C); Tao the air-out temperature (°C); Tas is the air temperature at saturation.

Crop parameter:

The crop parameter measured included the plant length and diameter, number and width of leaves, length and diameter of fruits, fresh and dry matter weight and crop yield.

2.2. Equipment and materials

The specific equipment and materials used for the purpose of conducting the experimental work included the following:

Nine plastic-film greenhouses, of the tunnel type, were used. The general specifications of each greenhouse cover double layers of polyethylene, dimensions (38 m length × 10 m width × 4.1 m height) and the frames galvanized iron.

Three different types of evaporative cooling pads were used, namely: celdek pads are made of a plywood and galvanized iron frame and a cooling pad made of fluted cellulose sheets that are glued together. Its material is chemically impregnated with special compounds to prevent rot and ensure a long service life. The general specifications of the celdek pad system are dimensions (6 m width × 2 m height × 10 cm thickness) in galvanized steel it has water system components source of water, pump, pipes, gutter and tank.

Straw pads are made of plywood and galvanized iron frame and the fitted pads are made of straw fiber contained in plastic nets, and they are similar to those used on evaporative cooling conditioners dimensions (6 m width × 2 m height × 10 cm thickness) in galvanized steel it has water system components source of water, pump, pipes, gutter and tank.

Sliced wood pads are made of a plywood and galvanized iron frame, and the fitted pads are made of sliced wood contained in wire nets. The length of the wood sliced was between 10 and 15 cm.

Exhaust fans were located on the greenhouse walls to draw out the greenhouse air, thus allowing fresh air to pass through the pads and into the greenhouse. Relative humidity and temperature meter were used to measure the relative humidity and temperature inside and outside of the greenhouse.

Pipe of irrigation system is 3/4 in. in diameter and 35 m length was used for the irrigation of the test crop in the greenhouses the pipe has 70 nozzles 50 cm apart and is connected with the water source pump.

Cucumber (*Cucumis sativus*), was used as a test crop to evaluate the performance of evaporative cooling pads and their effect on temperature and humidity for off-season growing of crops. Cucumber is a winter crop, grows rapidly between 25 and 30 °C at low relative humidity (Ahmed, 1988).

Table 1 Temperature inside and outside the greenhouse.

Treatment	Temperature (°C)		
	at 8 am	at 1 pm	at 6 pm
Straw pads (SP)	25.10 b	30.73 d	27.40 d
Celdek pads (CP)	25.77 b	31.87 c	29.00 c
Sliced wood pads (SWP)	26.39 b	32.97 b	30.89 b
Outside	32.74 a	42.50 a	36.30 a
SE ±	1.62	0.32	0.46
CV%	4.12	1.73	2.45

Note: Means in the same column(s) followed by the same letters are not significantly different according to Duncan's Multiple Range Test (DMRT).

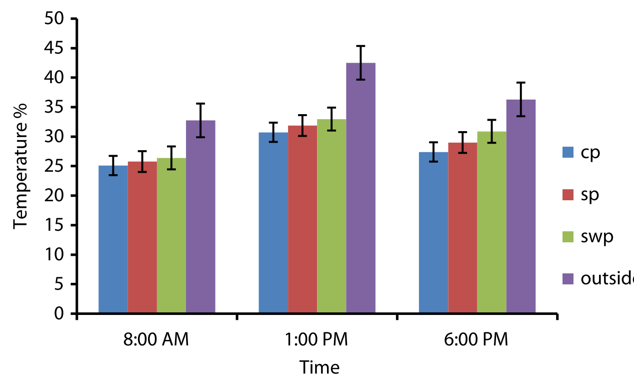

Figure 1 Temperature inside and outside the greenhouse at 8 am, 1 pm and 6 pm.

3. Results and discussion

This research work was conducted to evaluate the performance of three types of evaporative cooling pads [straw pads (SP), celdek pads (CP) and sliced wood pads (SWP)] for summer cooling in greenhouses. The performance evaluation included temperature, relative humidity and saturation efficiency.

Moreover, a test crop (cucumber) was used to evaluate the effectiveness of the different types of evaporative cooling pads on off-season production of crops. The crop parameters studied included stem length and diameter, leaves number and width, fruit length and diameter, fresh and dry weight of fruit and crop yield.

Environmental parameter:

Results of temperature obtained from inside the greenhouses with different types of evaporative cooling pads, as well as for the conditions outside the greenhouses, at 8 am are shown in Table 1 and Fig. 1.

The analysis of variance of the results showed that there was no significant difference ($P = 0.05$) in temperature between the three types of evaporative cooled greenhouses; however, the greenhouse with straw pads gave the lowest temperature (25.10 °C) while the one with sliced wood pads gave the highest (26.36 °C). Moreover, the analysis of variance showed that there was a significant difference ($P = 0.05$) in temperature between the conditions inside and outside the greenhouses. The conditions outside the greenhouses had the highest temperature (32.74 °C). This result is consistent with the findings of Nimje and Shyam (1993) who reported that the temperature outside the greenhouse at 8 am in the morning was relatively high due to the fact that the greenhouses conserve their coolness during the night and protects their inside from the short wave radiations in the morning.

Results of temperature obtained from the greenhouses with different types of evaporative cooling pads, as well as for the conditions outside the greenhouses, at 1 pm are shown in Table 1 and Fig. 1.

The analysis of variance of the results showed that there were significant differences ($P = 0.05$) between all treatments. The greenhouse with straw pads gave the lowest temperature (30.73 °C) followed by the greenhouse with celdek pads (31.87 °C) and the greenhouse with sliced wood pads (32.97 °C), while outside conditions gave the highest temperature (42.50 °C). The results could be attributed to the evaporative cooling effect of the pads, and the presence of a two-layer polyethylene covering of the greenhouses which created an air space and insulated the inside. Both factors increased the temperature difference between the inside and the outside of the greenhouses. Raymond (2006) obtained similar results.

The results of temperature obtained from the greenhouses with different types of evaporative cooling pads, as well as for the conditions outside the greenhouses, at 6 pm are shown in Table 1 and Fig. 1. The analysis of variance of the results showed that there were significant differences ($P = 0.05$) in temperature within and outside the greenhouses. The Duncan's multiple range test for mean separation showed that the temperature in the greenhouse with straw pads was the lowest (27.40 °C) followed by the one with celdek pads (29.00 °C) and the one with sliced wood pads (30.90 °C), while the temperature outside the greenhouses was the highest (36.30 °C) as expected.

3.1. Relative humidity inside and outside the greenhouse

The results obtained for relative humidity from the greenhouses with different types of evaporative cooling pads, as well as for the conditions outside the greenhouses, at 8 am are shown in Table 2 and Fig. 2. The analysis of variance showed that there were significant differences ($P = 0.05$) between all treatments. The greenhouse with sliced wood pads gave the lowest relative humidity (39.56%) followed by the one with celdek pads (42.75%) and the one with straw pads (51.16%). However, conditions outside the greenhouses gave the least relative humidity (22.50%). The high value of relative humidity obtained for the greenhouse with straw pads could be attributed to the relatively higher ability of those pads in reducing the temperature at that time of the day, and their better ventilation. The above results are in line with the findings of Nimje and Shyam (1993).

The results obtained for relative humidity inside the greenhouses with different types of evaporative cooling pads, as well as for the conditions outside the greenhouses, at 1 pm are shown in Table 2 and Fig. 2. The analysis of variance showed that there were significant differences ($P = 0.05$) between all treatments. The greenhouse with sliced wood pads gave the lowest relative humidity (32.97%) followed by the one with celdek pads (38.80%) and the one with straw pads (40.73%). However, conditions outside the greenhouses gave the least relative humidity (19.90%). Due to the evaporative cooling effect and proper ventilation, the relative humidity was always higher inside the greenhouse compared to the outside conditions. Nimje and Shyam (1993) indicated that maintaining proper relative humidity in the greenhouse or growing area can be very difficult during hot, dry summer days.

The results for relative humidity obtained from the greenhouses with different types of evaporative cooling pads, as well as for the conditions outside the greenhouses, at 6 pm are shown in Table 2 and Fig. 2. The analysis of variance showed that there was no significant difference ($P = 0.05$) in relative humidity between the three types of evaporative cooled greenhouses; however, the greenhouse with sliced wood pads gave the lowest relative humidity (36.02%), while the one with straw pads gave the highest (37.04%). Moreover, the analysis of variance showed that there was a significant difference ($P = 0.05$) in relative humidity between the conditions inside and outside the greenhouses. The conditions outside the greenhouses had the least relative humidity (20.33%). The above results agreed with the findings of Bartok (1990) and Rane (1989).

Table 2 Relative humidity inside and outside the greenhouse.

Treatment	Relative humidity (%)		
	at 8 am	at 1 pm	at 6 pm
Straw pad (SP)	57.16 a	40.73 a	37.04 a
Celdek pads (CP)	42.75 b	38.87 b	36.64 a
Sliced wood pads (SWP)	39.56 c	32.97 c	36.02 a
Outside	22.50 d	19.90 d	20.33 b
SE ±	0.70	0.32	1.98
CV%	2.88	1.73	6.88

Note: Means in the same column(s) followed by the same letters are not significantly different according to Duncan's Multiple Range Test (DMRT).

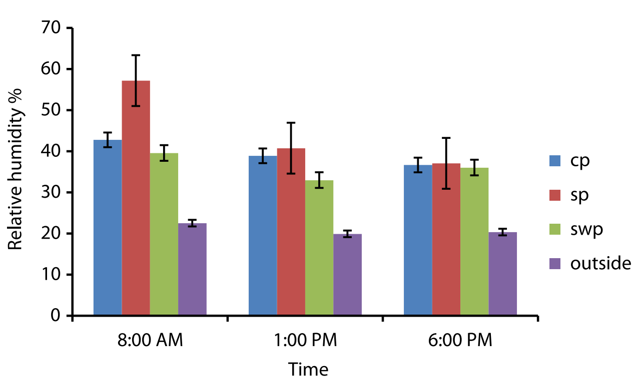

Figure 2 Relative humidity inside and outside the greenhouse at 8 am, 1 pm and 6 pm.

3.2. Saturation efficiency of evaporative cooling pads

The results of the saturation efficiency inside the greenhouses for the three types of evaporative cooling pads, using Eq. (1), are shown in Table 3 and Fig. 3.

The analysis of variance of the results showed that there was a significant difference ($P = 0.05$) in saturation efficiency between the three types of evaporative cooled greenhouses. The greenhouse cooled by straw pads gave the least value of saturation efficiency (76%), while the one cooled by sliced wood pads gave the highest value (90%). The poor performance of the straw pads could be attributed to the increased relative humidity coupled with plant evapotranspiration and reduced ventilation efficiency. On the other hand, the much better performance of the sliced wood pads could be attributed to the well designed, properly installed and operated evaporative cooing system. These results are in line with the findings of Nimje and Shyam (1993) and Bucklin (2004).

Table 3 Saturation efficiency (μ%) for the different pad types.

Pads types	Tia	Tao	Tas	μ%	Means
Straw pads (SP)	27.0	22.5	21.0	76.0	79.32 c
Celdek pads (CP)	29.0	24.5	22.5	85.0	81.60 b
Sliced wood pad (SWP)	30.0	25.5	25.0	90.0	85.76 a
SE ±	0.82				
CV%	8.47				

Note: Means in the same column(s) followed by the same letters are not significantly different according to Duncan's Multiple Range Test (DMRT).
μ = cooling efficiency (%).
Tai = air-in temperature (°C).
Tao = air-out temperature (°C).
Tas = air temperature at saturation.

3.3. Crop production parameters

Stem length and diameter and leaves number and width:

The results obtained for stem length and diameter under different treatments are shown in Table 4 and Fig. 4. The analysis of variance of the results showed that there were significant differences ($P = 0.05$) in stem length and diameter between the treatments. It was found that the stem length and diameters (96 and 1.44 cm, respectively) under the conditions of the greenhouse cooled by straw pads were the lowest compared to the other greenhouses, which could be attributed to increased relative humidity and reduced temperature. This result is in line with the findings of Ernst (2004) who indicated that a high relative humidity may cause weakening of the growth of a crop.

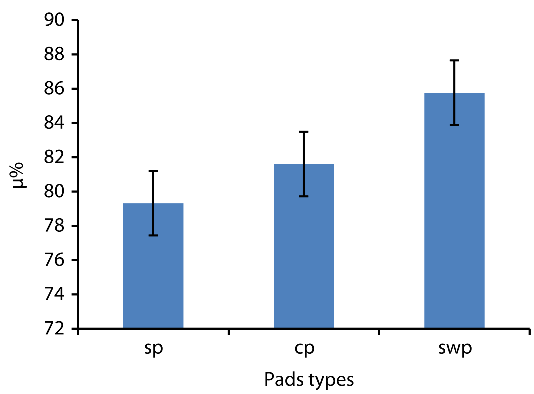

Figure 3 Saturation efficiency inside the greenhouse ($\mu\%$) for the different pad types.

Table 4 Stem length and diameter and leaves number and width inside and outside the greenhouses.

Treatment	Length of stem (cm)	Stem diameter (cm)	Leaves number	Leaves width (cm)
Straw pads	96.0 c	1.44 d	30 c	5.5 c
Celdek pads	175.5 b	2.50 c	55 b	7.8 b
Sliced wood pads	210.5 a	3.80 b	75 a	10.4 a
Outside	20.0 d	5.10 a	9 d	3.0 d
SE ±	0.43	0.35	0.45	0.70
CV%	13.42	21.23	11.66	12.43

Note: Means in the same column(s) followed by the same letters(s) are not significantly different according to Duncan's Multiple Range Test.

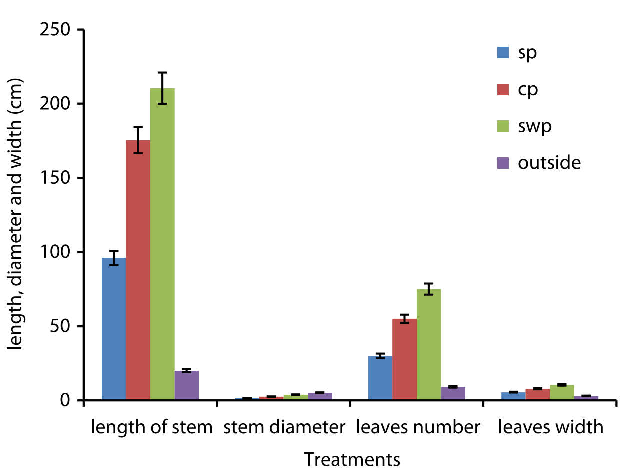

Figure 4 Stem length and diameter and leaves numbers and width inside and outside the greenhouses.

The conditions inside the greenhouse cooled by sliced wood pads gave the highest plant height and stem diameter (210 and 3.8 cm, respectively) compared to the other greenhouses. This result may be due to low relative humidity and temperature, as well as proper ventilation. Comparing the results of stem length and diameter inside and outside of the greenhouses, it was found that plants under outside conditions were the shortest (20 cm), but have the largest stem diameter (5.1 cm), which could be attributed mainly to the effects of the conditions outside the greenhouses, which were detrimental to stem length and favorable to stem diameter growth. Raymond (2006) indicated that the detrimental effects of high temperature on plant growth include reduced stem length, reduced leaf size, delayed flowering, reduced flower size, flower bud abortion, and reduced growth rate.

The result obtained for plant leaves number and width under different treatments is shown in Table 4 and Fig. 4. The analysis of variance of the results indicated that there were significant differences ($P = 0.05$) in plant leaves number and width between the treatments. The greenhouse cooled by sliced wood pads gave the highest leaves number and width (75 and 10.4 cm, respectively), while conditions outside the greenhouses gave the least results (9.0 and 3.0 cm). The greenhouse cooled by straw pads gave the lowest leaves number and width (30 and 5.5 cm, respectively) compared to the other two greenhouses. These results are in line with the findings of Chauhan (1972).

3.4. Fruit length and diameter and fresh fruit dry matter weight

The results obtained for fruit length and diameter under different treatments are shown in Table 5 and Fig. 5.

The analysis of variance of the results showed that there were significant differences ($P = 0.05$) in fruit length and diameter between the treatments. The greenhouse cooled by sliced wood pads gave the highest fruit length and diameter (17.3 and 7.5 cm, respectively), while outside conditions gave the least results (5.3 and 2.3 cm). The greenhouse cooled by straw pads gave the lowest fruit length and diameter (13.4 and 3.3 cm, respectively) as compared to the other two greenhouses. Nimje and Shyam (1993) reported that the fruit length and diameter were higher inside the greenhouse than outside the open field in tropical and sub tropical regions.

The results obtained for fruit weight and dry matter under different treatments are shown in Table 5 and Fig. 6.

The analysis of variance of the results indicated that there were significant differences ($P = 0.05$) in fruit weight and dry matter among the treatments. The greenhouse cooled by sliced wood pads gave the highest fruit weight and dry matter (90.3 and 74.6 g, respectively,), while outside conditions gave the least results (30 and 17.8 g). The greenhouse cooled by straw pads gave the lowest fruit weight and dry matter (50.6 and 34.0 g, respectively) when compared to the other two greenhouses. These results could be attributed to the variabil-

Table 5 Fruit length and diameter, fresh and dry matter weight and crop yield inside and outside the greenhouses.

Treatment	Fruit diameter (cm)	Fruit length (cm)	Fruit weight (g)	Dry matter (g)	Yield per plant (g)
Straw pads	3.30 c	13.40 c	50.60 c	34.00 c	350 c
Celdek pads	5.50 b	15.50 b	80.50 b	69.30 b	665 b
Sliced wood	7.50 a	17.30 a	90.30 a	74.60 a	820 a
Outside	2.30 d	5.30 d	30.00 d	17.80 d	150 d
SE ±	0.97	0.63	0.15	0.15	1.02
CV%	16.3	4.88	12.33	14.37	15.07

Note: Means in the same column(s) followed by the same letters(s) are not significantly different according to Duncan's Multiple Range Test (DMRT).

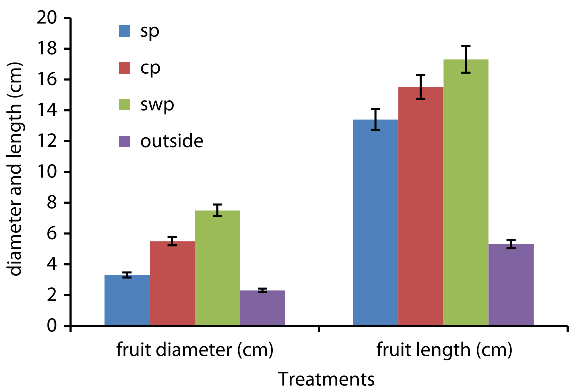

Figure 5 Fruit diameter and length inside and outside the greenhouses.

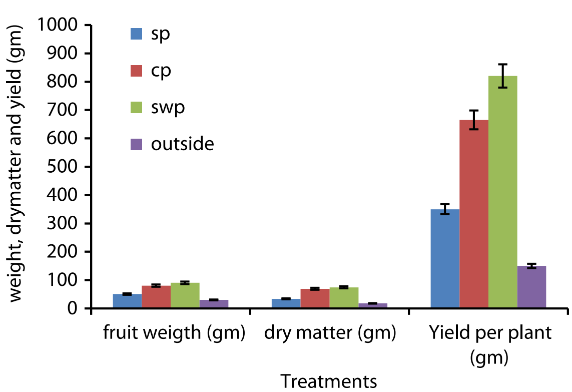

Figure 6 Fruit weight and dry matter and yield inside and outside the greenhouses.

ity in environmental conditions between the treatments. The result are in line with the findings of Marcelis and Eijer (1996) who reported that fruit weight and dry matter content are linked directly to the climatic conditions of temperature, relative humidity, carbon dioxide concentration and daily light interval.

3.5. Yield per plant

The results obtained for yield per plant under different treatments are shown in Table 5 and Fig. 6.

The analysis of variance of the results showed that there were significant differences ($P = 0.05$) in crop yield between treatments. The greenhouse cooled by sliced wood pads gave the highest crop yield per plant (820 g), while outside conditions gave the lowest result (150 g). The greenhouse cooled by straw pads gave the lowest yield per plant (350 g) when compared to the other two greenhouses. These results were expected because of the different environmental conditions under the different treatments, and are in line with findings of Medany et al. (1999), who reported that the fruit yield was about two times higher inside the greenhouse than the open field due to warm and humid weather inside.

4. Conclusions

From the totality of the results obtained from this research work it could be concluded that:

- There was no significant difference in temperature between the three types of evaporative cooled greenhouses at 8 am. Therefore, similar results were obtained with the use of different types of evaporative cooling pads.
- There were significant differences in temperature between the different types of greenhouses at both 1 pm and 6 pm. The greenhouse with sliced wood pads gave the highest temperature, while that with straw pads gave the lowest.
- Conditions outside the greenhouses, with regard to temperature, were significantly different from those inside and gave higher temperatures at all three times of readings.
- There were significant differences in relative humidity between the different types of greenhouses at both 8 am and 1 pm, but not at 6 pm. The greenhouse with sliced wood pads gave the lowest relative humidity at all times, while the one with straw pads gave the highest.
- Conditions outside the greenhouses, with regard to relative humidity, were significantly different from those inside, and gave the least relative humidity at all three timings.
- There was a significant difference in saturation efficiency between the three types of cooling pads, such that the sliced wood pads gave the highest saturation efficiency and the straw pads gave the lowest.
- There were significant differences in crop production traits between the different types of greenhouses. The greenhouse with sliced wood pads resulted in the highest stem length and diameter, number and width of leaves, fruit length and diameter, weight of fresh and dry matter of fruit, as well as yield per plant. On the other hand, the greenhouse with straw pads gave the lowest results.

- Conditions outside the greenhouses, with regard to crop production parameters, were significantly different from those inside, and gave the least values for all measured traits tested except for plant stem diameter, which was higher than any value obtained.

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